Systematic errors and combination of individual CRF solutions in the framework of the international pilot project for the next ICRF

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Abstract

A new international Pilot Project for the redetermination of the ICRF was initiated by the International VLBI Service for Geodesy and Astrometry (IVS) in January 2005. The purpose of this project is to compare the individual CRF solutions and to analyze their systematic and random errors with focus on the selection of the optimal strategy for the next ICRF realization. Eight radio source catalogues provided by the IVS Analysis Centers GA, SHAO, DGFI, GIUB-BKG, JPL, MAO NANU, GSFC, USNO were analyzed. In present study, four analytical models were used to investigate the systematic differences between solutions: solid rotation, rotation and deformation (IERS method), and expansion in orthogonal functions: Legendre-Fourier polynomials and spherical functions. It was found that expansions by orthogonal function describe the differences between individual catalogues better than the two former models. Finally, the combined CRF was generated. Using the radio source positions from this combined catalogue for estimation of EOP has shown improvement of the uncertainty of the celestial pole offset time series.

1 Introduction

Celestial reference system (CRF) as realized by a set of coordinates of selected celestial objects is widely used for numerous astronomy, navigation, time and other measurements. The CRF accuracy and stability are all-important for successful solution of all these tasks. For millennia, the CRF was based on optical observations and star positions. With establishment of new observing technique, very long baseline interferometry (VLBI), much more accurate CRF realization became available. In 1998, the CRF based on the positions of extragalactic radio sources has been adopted by IAU (International Astronomy Union) as the fundamental celestial reference frame, replacing the FK5 optical frame (Arias et al. 1995, Ma et al. 1998).

After publishing of the first VLBI RSC, attempts was made to improve the accuracy of radio-band CRF by means of constructing of combined catalogues, as it was customary for optical astronomy, where fundamental catalogues served as an international standard for astrometry and other measurements on the sky. Different methods were used to obtain a combined RSC, e.g. Walter (1989a,b), Yatskiv & Kur'yanova (1990), Kur'yanova & Yatskiv (1993). Also, till 1995, IERS (International Earth Rotation Service) used derived combined RSC for maintenance of the IERS Celestial Reference Frame.

However, starting from 1996, new CRF realization was adopted by the IERS, and further approved by the IAU in 1998. The first realization of the ICRF was based on the refined analysis of VLBI observations made at the NASA Goddard Space Flight Center, USA (Ma et al. 1998). All the 608 radio sources included in the ICRF was divided into three groups: 212 *defining* sources whose coordinates are supposed to be kept in the future realizations to maintain the ICRF orientation, 294 *candidate* sources not sufficiently monitored, and 102 **other** sources for improving the sky coverage. In 1999 and 2004, two ICRF extensions ICRF-Ext.1 (Ma 2001) and ICRF-Ext.2 (Fey et al. 2004) have been published. In those versions, the positions of 212 *defining* sources were kept the same as obtained in the first ICRF. It should be noted that both ICRF extensions were obtained in a manner similar to the first realization, *i.e.* as a result of analysis of the VLBI observations at a single analysis center. The latest ICRF realization, ICRF-Ext.2, is hereafter referred to as ICRF.

In the end of 2004, joint pilot project of the IERS and the IVS (International VLBI Service for Geodesy and Astrometry, Schlueter et al. 2002) was initiated (Ma 2004, Call for Participation). One of the main goals of the project was to seek after possible ways to improve the existing ICRF. Large experience accrued by the optical astrometry during centuries shows that combining catalogues of the star positions have better random and systematic accuracy than individual catalogues. In particular, the latter can be affected by the systematic errors caused by algorithms and software used for data processing. Hopefully, a combining procedure can be used to mitigate influence of errors of individual RSC. Another main goal of the Pilot Project is to develop new methods of comparison of RSC adequate to the modern level of their precision and accuracy, in other words, their random (stochastic) and systematic errors.

In this paper, the work was made in four steps.

1. Analysis of the random and systematic errors of individual (input) catalogues, and a choice of the most adequate method of representation of the systematic differences between catalogues.

2. Determination of the systematic differences between the input catalogues and ICRF.

3. Construction of a combined catalogue in the ICRF system (stochastic improvement of the ICRF).

4. Construction of the final combined catalogue (systematic improvement of the ICRF).

First, we searched after optimal method of representation of the systematic errors of the RSC. Then we investigated a possibility of improving the ICRF by means of combining individual RSC. Four methods of representation of the systematic part of differences in the RSC have been examined on the basis of comparison of the residual differences in the radio source coordinates. Eight individual radio source catalogues, and ICRF were used in this study. After the most accurate method had been chosen, it was used to compute the systematic differences between the individual catalogues and ICRF. Finally, these differences were used in the procedure of construction of combined RSC. Thus obtained combined catalogue was tested by means of computation of celestial pole offset time series with both combined and ICRF RSC. Result of this test showed improvement of the scatter of the time series when combined RSC is used.

2 Input catalogues

Input catalogues used in this study were submitted by eight IVS Analysis Centers: AUS (Geoscience Australia), BKG (Bundesamt für Kartographie und Geodäsie, Germany), DGFI (Deutsches

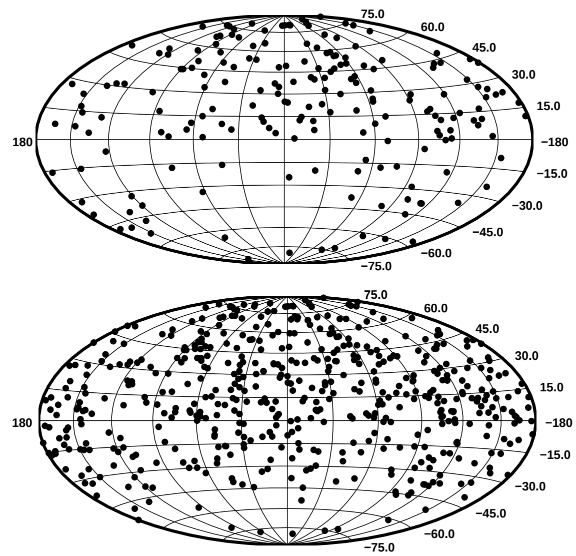

Figure 1: Sky distribution for 196 *defining* (*top*) and all 525 sources (*bottom*) common for the input catalogues.

Geodätisches Forschungsinstitut, Germany), GSFC (NASA Goddard Space Flight Center, USA), JPL (Caltech/NASA Jet Propulsion Laboratory, USA), MAO (Main Astronomical Observatory of National Academy of Sciences of Ukraine), SHAO (Shanghai Astronomical Observatory, China), USNO (U. S. Naval Observatory, USA). Brief description of the input catalogues is given in Table 1.

Usually, investigation of the systematic differences between catalogues is made using some set of reference sources common for compared catalogues. Comparison of the lists of radio sources included in the input catalogues showed that there are 525 sources present in all the catalogues, 196 of them belong to the list of 212 ICRF *defining* sources. This should be mentioned that we took into account only the sources which have at least 15 observations in 2 sessions. After such a selection, the total number of sources present in all the input catalogues amounts to 968. Fig. 1 shows the distribution of common sources over the sky.

Both source lists, as well as other subsets of 525 sources, can be used as reference for analysis of the systematic differences between catalogues. All the computations described below were carried out for both 196 and 525 sources. At this paper, we present only the results obtained with the first list of 196 sources. Although definite differences in results were found, the main conclusions made in this study do

Table 1: Input catalogues. The last column shows number of the sources in the catalogue and number of reference sources used to tie the orientation of the catalogue to ICRF.

Center	Software	Time span	Number of	
		month/year	delays	sources
AUS	OCCAM	11/1979 – 12/2004	3208197	737(207)
BKG	Calc/Solve	01/1980 – 01/2005	4031453	748(212)
DGFI	OCCAM	01/1980 – 01/2005	3650771	686(199)
GSFC	Calc/Solve	08/1979 – 01/2005	4574189	954(212)
JPL	MODEST	10/1978 – 01/2005	3575847	734(2)
MAO	SteelBreeze	10/1980 – 01/2005	3773765	685(25)
SHAO	Calc/Solve	04/1980 – 01/2005	4431503	813(212)
USNO	Calc/Solve	09/1979 – 01/2005	4252684	943(207)

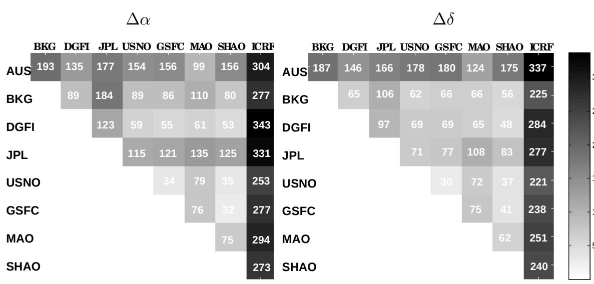

Figure 2: WRMS differences between the input catalogues and ICRF. Unit: μas.

not depend on the reference source list.

Weighted root-mean-square (WRMS) differences of the radio source coordinates between the input catalogues and ICRF are shown in Fig. 2 (μas stands for microarcseconds). One can see from Fig. 2 WRMS differences have the least values for catalogues computed with Calc/Solve software, both for intercomparison of these catalogues and their comparison with ICRF. The latter most probably is caused by the fact that the ICRF was constructed using Calc/Solve software. Large WRMS differences between JPL and other catalogues may be caused by its orientation to ICRF which has been defined by only two reference sources, unlike other catalogues, for which much longer lists of reference sources were used. Catalogue AUS shows the greatest differences with other catalogues, probably, because it is the only catalogue constructed using the Least Squares Collocation method, while other Analysis Centers used conventional Least Squares. One can see that the DGFI catalogue, also constructed using OCCAM software, but Least Squares version, does not stand out against other catalogues.

The WRMS differences between the input catalogues themselves may be not valuable, especially when they are caused by the difference in orientation of the catalogues' axes, which can be easily accounted for during combination. More interesting fact is that all the input catalogues demonstrate rather large differences with the ICRF, which may indicate significant systematic errors in the latter. This preliminary conclusion will be confirmed by the analysis of the systematic differences given below.

3 Analytical representation of the systematic differences

Suppose, we have two catalogues of position of celestial sources given as set of spherical coordinates α_{1i}, δ_{1i} and α_{2i}, δ_{2i}, where i is the source number. Denote the differences between spherical coordinates of the i-th object given in two catalogues as $\Delta\alpha_i = \alpha_{1i} - \alpha_{2i}, \Delta\delta_i = \delta_{1i} - \delta_{2i}$. The aim of an analytical representation of the systematic differences between two catalogues is to obtain formulae

$$\begin{array}{l} \Delta\alpha = f_\alpha(\alpha,\delta)\,, \\ \Delta\delta = f_\delta(\alpha,\delta)\,, \\ \text{or} \\ \left\{ \begin{array}{c} \Delta\alpha \\ \Delta\delta \end{array} \right\} = f(\alpha,\delta)\,, \end{array} \tag{1}$$

which provides minimum residuals between $\Delta\alpha_i$, $\Delta\delta_i$ observed and computed analytically. In fact, such a representation of the systematic differences is a kind of a low-pass filter, which allow us to smooth stochastic errors in coordinates. Having such a representation, one can reduce a RSC to the system of another catalogue.

In this section, we compare four methods of analytical representation of the systematic differences between radio source positions given in various catalogues. Those methods are: simple rotation around three Cartesian axes hereafter referenced to as "R", rotation plus deformation used by IERS ("RD"), Brosche's method ("B") and expansion in Legendre-Fourier functions ("LF").

It should be noted that in usual astrometric practice differences between source positions in right ascension are used as $\Delta\alpha\cos\delta$, which reflects the geometry of the celestial sphere. However, hereafter we use $\Delta\alpha$ because IERS's method is formulated only for this type of differences. Other method listed below can be easily adapted to $\Delta\alpha\cos\delta$.

3.1 Simple rotation

Two given catalogues realize two Cartesian coordinate systems $X_1Y_1Z_1$ and $X_2Y_2Z_2$. Then differences between source positions in two catalogues can be represented as the result of rotation of the second coordinate system with respect to the first coordinate system about axes XYZ by three angles A_1, A_2, A_3. Then the systematic differences between two catalogues can be expressed as (Walter & Sovers, 2000)

$$\begin{aligned} \Delta\alpha &= A_1\tan\delta\cos\alpha + A_2\tan\delta\sin\alpha - A_3\,, \\ \Delta\delta &= -A_1\sin\alpha + A_2\cos\alpha\,. \end{aligned} \tag{2}$$

3.2 Rotation with deformation

This method of representation of the systematic differences between radio source catalogues was proposed by Arias and Bouquillon (2004), and it is used by the IERS since 1995. The authors added to (2) three supplement terms to account for some specific errors of VLBI catalogues. In this method, the systematic differences between two catalogues are approximated by

$$\begin{aligned} \Delta\alpha &= A_1\tan\delta\cos\alpha + A_2\tan\delta\sin\alpha - A_3 + D_\alpha\delta\,, \\ \Delta\delta &= -A_1\sin\alpha + A_2\cos\alpha + D_\delta + B_\delta\,. \end{aligned} \tag{3}$$

3.3 Brosche's method

In this method, as well as in the next one, an expansion of the differences in source positions between catalogues in orthogonal functions is used. Large experience collected by the optical astrometry proved that such an expansion provides the highest accuracy of the representation of the systematic errors of catalogues of celestial source positions. In this case, the general representation of the differences (1) is given by

$$\left\{ \begin{array}{c} \Delta\alpha \\ \Delta\delta \end{array} \right\} = \sum_{j=0}^{g} b_j Y_j(\alpha,\delta)\,, \tag{4}$$

where b_j are the coefficient to be found from analysis of the differences. According to Brosche (1966)

$$Y_j(\alpha,\delta) = \begin{cases} P_{n0}(\delta), & k=0, l\neq 1\,, \\ P_{nk}(\delta)\sin(k\alpha), & k\neq 0, l=0\,, \\ P_{nk}(\delta)\cos(k\alpha), & k\neq 0, l=1\,, \end{cases} \tag{5}$$

where P_{nk}, associated Legendre polynomials are given by

$$P_{nk}(\delta) = \cos^k\delta \left[\sin^p\delta + \sum_{\mu=1}^{[p/2]} \frac{(-1)^\mu \prod\limits_{\nu=0}^{2\mu-1}(p-\nu)}{\prod\limits_{\nu=1}^{\mu} 2\nu(2n-2\nu+1)} \sin^{p-2\mu}\delta \right]. \tag{6}$$

where $p = n-k$, $[p/2]$ is entier of $p/2$, $n = 0,1,\ldots$, $k = 0,1,2,\ldots,n$, $j = n^2+2k+l-1$.

3.4 Legendre-Fourier functions

Bien et al. (1978) has proposed to use another set of orthogonal functions for better representation of systematic differences between catalogues, especially in the polar regions. In this case (4) is given by

$$\begin{aligned} \left\{ \begin{array}{c} \Delta\alpha \\ \Delta\delta \end{array} \right\} &= \sum_{nkl} b_{nkl} Y_{nkl}(\alpha,\delta)\,, \\ Y_{nkl}(\alpha,\delta) &= R_{nkl} L_n(\sin\delta) F_{kl}(\alpha)\,. \end{aligned} \tag{7}$$

Here we omit the Hermite function included in the original expression of Bien et al. (1978) to account for the source brightness. Commonly speaking, such a dependence may do exist in the case of VLBI observations too, and it worth separate investigating. Legendre polynomials can be computed using recursion

$$\begin{aligned} &L_0 = 1\,, \\ &L_1 = \sin\delta\,, \\ &L_{n+1}(\sin\delta) = \frac{2n+1}{n+1}\sin\delta\, L_n(\sin\delta) - \frac{n}{n+1} L_{n-1}(\sin\delta)\,, \\ &\qquad n = 2,3,\ldots\,. \end{aligned} \tag{8}$$

Fourier functions are given by

$$F_{kl}(\alpha) = \begin{cases} 1, & k=0, \quad l=-1\,, \\ \cos(kl\alpha), & k\neq 0, \quad l=1\,, \\ \sin(-kl\alpha), & k\neq 0, \quad l=-1\,. \end{cases} \tag{9}$$

Lastly, normalizing functions are given by

$$R_{nkl} = \sqrt{2n+1} \begin{cases} 1, & k=0\,, \\ \sqrt{2}, & k\neq 0. \end{cases} \tag{10}$$

All the four methods described above were applied to the differences between each of eight input catalogues and ICRF for 196 common *defining* sources (see section refinput. For this purpose, the coefficients of (2), (3), (5), (7) were found by means of Least Squares adjustment. After that we computed the residuals between original differences and those computed by formulae (2), (3), (5), (7). The results are presented in Fig. 3 and Table 2. Representation with the Brosche's model is not shown in Fig. 3 because corresponding surface practically coincides with the Legendre-Fourier expansion. One can see that expansion in Legendre-Fourier functions provides the least residuals, it i.e. most accurate representation of the systematic differences between catalogues. Expansion in spherical functions (Brosche's method) gives worse accuracy. As to the first two methods, they seem to be not adequate to actual errors of modern RSC.

4 Combined catalogue in the ICRF system

At the next step, the systematic differences between the input catalogues and ICRF found by the LF method as described in the previous section were applied to all of the input catalogues with the view to transforming them to the ICRF system. After that, the coordinates of all the sources in transformed catalogues were averaged with weights depending on the formal errors of coordinates. In result, the combined catalogue RSC(PUL)07C01 was constructed. This catalogue containing all the 968 sources present in the input catalogues can be considered as a stochastic improvement of the ICRF. Fig. 4 shows the WRMS differences between the input catalogues transformed to the ICRF system and RSC(PUL)07C01.

Comparing Fig. 2 and 4, one can conclude that the differences between the input catalogues contain not only systematic part described by analytical representation, but also, in some cases, significant stochastic and/or high-frequency components.

Fig. 5 shows the systematic difference between combined catalogue RSC(PUL)07C01 and ICRF. One can see that the catalogue RSC(PUL)07C01 represents the ICRF system at a level of about 10 μas.

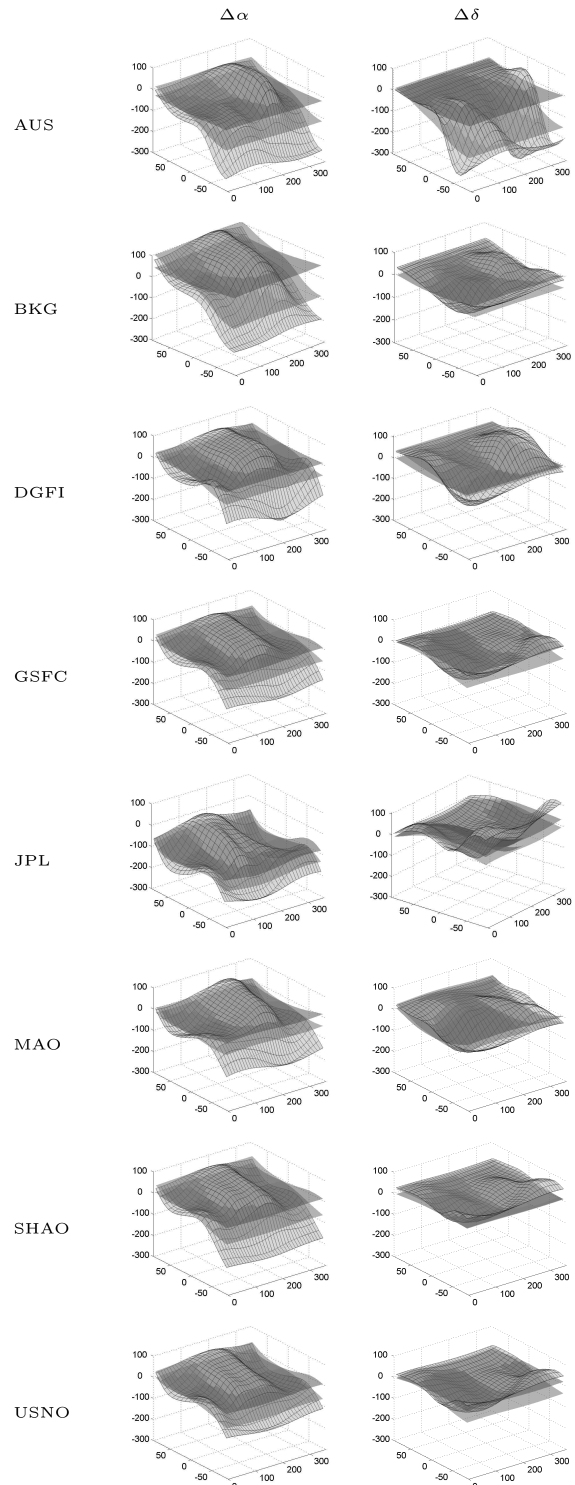

Figure 3: Analytical representation of the differences between the input catalogues and ICRF: R (dark grey), RD (grey), LF (light grey). Original differences are shown in black lines. Horizontal axes show right ascension (*right*) and declination (*left*) in degrees. Unit: μas.

5 Final combined catalogue

Final combined catalogue was constructed in the following way. Let us call the system of a catalogue the set of coefficients of Legendre-Fourier functions obtained for given catalogue. Thus we have eight sys-

Table 2: WRMS residuals between the input catalogues and ICRF before (Raw) and after approximation of the systematic differences (see notation of the methods in text). Results related to the LF method providing the best approximation are shown in bold. Unit: μas.

	AUS	BKG	DGFI	JPL	USNO	GSFC	MAO	SHAO
					$\Delta\alpha$			
Raw	304	277	343	331	253	277	294	273
R	301	271	342	308	249	274	286	271
RD	299	265	342	308	247	273	285	270
B	170	177	237	238	172	191	203	193
LF	**106**	**125**	**164**	**172**	**122**	**144**	**152**	**145**
					$\Delta\delta$			
Raw	337	225	284	277	221	238	251	240
R	337	225	284	273	221	238	251	240
RD	333	224	283	273	221	237	251	239
B	180	159	178	182	152	158	169	166
LF	**111**	**109**	**112**	**127**	**104**	**106**	**134**	**111**

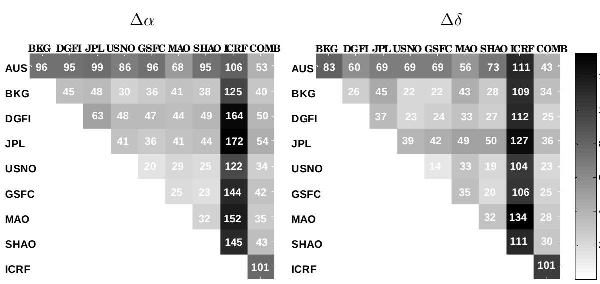

Figure 4: WRMS differences between the input catalogues transformed to the ICRF system and combined catalogue RSC(PUL)07C01. Unit: μas.

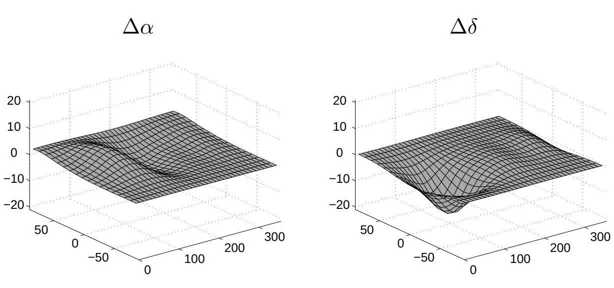

Figure 5: Differences between RSC(PUL)07C01 and ICRF. Horizontal axes show right ascension (*right*) and declination (*left*) in degrees. Unit: μas.

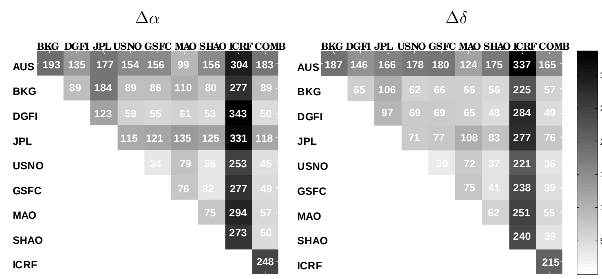

Figure 6: WRMS differences between the input catalogues and combined catalogue RSC(PUL)07C02. Unit: μas.

tems corresponding to the eight input catalogues. At the first iteration, these systems were averaged without weights. Then the WRMS differences between this average system and the systems of the input catalogues for the bins $10^\circ(\alpha) \times 5^\circ(\delta)$ were computed. Thus obtained WRMS were used for weighting of the input catalogues at the second iteration. Although we use different weights of the input catalogues for different bins, they are close for each catalogue. Final weights of the catalogues averaged over the sky are given in Table 3.

Thus computed average system was added to the first combined catalogue RSC(PUL)07C01. In result, final combined catalogue, RSC(PUL)07C02 have been obtained. It can be considered as both stochastic and systematic improvement of the ICRF. In Fig. 6, WRMS differences between the input catalogues and combined catalogue RSC(PUL)07C02 are shown, and Fig. 7 presents the systematic differences between the input catalogues and RSC(PUL)07C02.

Comparison of RSC(PUL)07C02 and ICRF is pre-

Table 3: Weights of the input catalogues applied during combination, averaged over the sky.

	AUS	BKG	DGFI	GSFC	JPL	MAO	SHAO	USNO
α	0.246	0.671	0.464	1.993	0.254	0.558	1.792	2.062
δ	0.205	1.220	0.586	1.921	0.446	0.541	1.459	1.927

Table 4: WRMS differences between celestial pole offset series computed with two CRF realization and IAU2000A model corrected for FCN contribution. Unit: μas.

Catalogue	X_c	Y_c
ICRF-Ext.2	103	100
RSC(PUL)07C02	98	98

sented in Fig. 8, which show the result of expansion of the differences between two catalogues in Legendre-Fourier functions. Results of this comparison lead us to the supposition that ICRF may have significant systematic errors.

6 Comparison with observations

It is important to assess an actual accuracy of obtained catalogue (as well as other CRF realizations). Unfortunately, existing methods of comparison of catalogues allow us to investigate only *differences* between catalogues. Here, we use a test, which can help us to get some independent estimate of the quality of our combined catalogue. For this purpose, we compute two celestial pole offset time series from processing of R1 and R4 IVS observing programs observed in the period 2002–2006 with two radio source catalogues, ICRF-Ext.2 and RSC(PUL)07C02. Then we compute the WRMS differences between computed celestial pole offsets and Free Core Nutation model. The result of this test presented in Table 4 shows clear improvement of the scatter of celestial pole offset estimates.

7 Conclusion

In this paper, we have constructed a new combined catalogue of radio source coordinates. For this study we used eight catalogues submitted by IVS Analysis Centers in the framework of the IERS/IVS Pilot Project on the future realization of ICRF.

First, we have examined four methods of analytical representation of systematic differences between catalogues of radio source coordinates. Representation by means of expansion in Legendre-Fourier functions is proved to be the most accurate method. Two methods usually used for comparison of radio source catalogues, simple rotation and rotation with deformation seem to be not suitable for investigation of modern radio source catalogues, and should be replaced by more adequate one.

Two combined radio source catalogues have been constructed. The first of them is obtained as weighted average of the input catalogues corrected for systematic differences with ICRF. It can be considered as stochastic improvement of the current realization of ICRF. Second combined catalogue have been obtained from the first one after applying the weighted average systematic difference between the input catalogues and ICRF, which allows one to account also for possible ICRF systematic errors.

To compare our combined catalogue with ICRF, we used two tests, which allow us to independently estimate the scatter of celestial pole offsets time series obtained from processing of VLBI observations using ICRF and combined catalogue. Both tests have showed improvement of the results.

The results obtained in this paper allow us to make a conclusion that ICRF-Ext.2 may have significant systematic errors, most probably caused by fixing the coordinates of 212 *defining* sources to its values obtained in the first ICRF version of 1995.

Further development of this study may include:

- More detailed analysis of stochastic and systematic errors of radio source catalogues.
- Estimation of possible impact of the high-frequency systematic errors in source position on the orientation of the catalogue axes.
- Analysis of the reasons of systematic differences between radio source catalogues.
- Careful selection of the input catalogues and reference sources.
- Elaboration of weighting method.
- Development of more sensitive methods of the assessment of the accuracy of CRF realizations.

It is also interesting to compare different methods of construction of combined catalogue of radio source

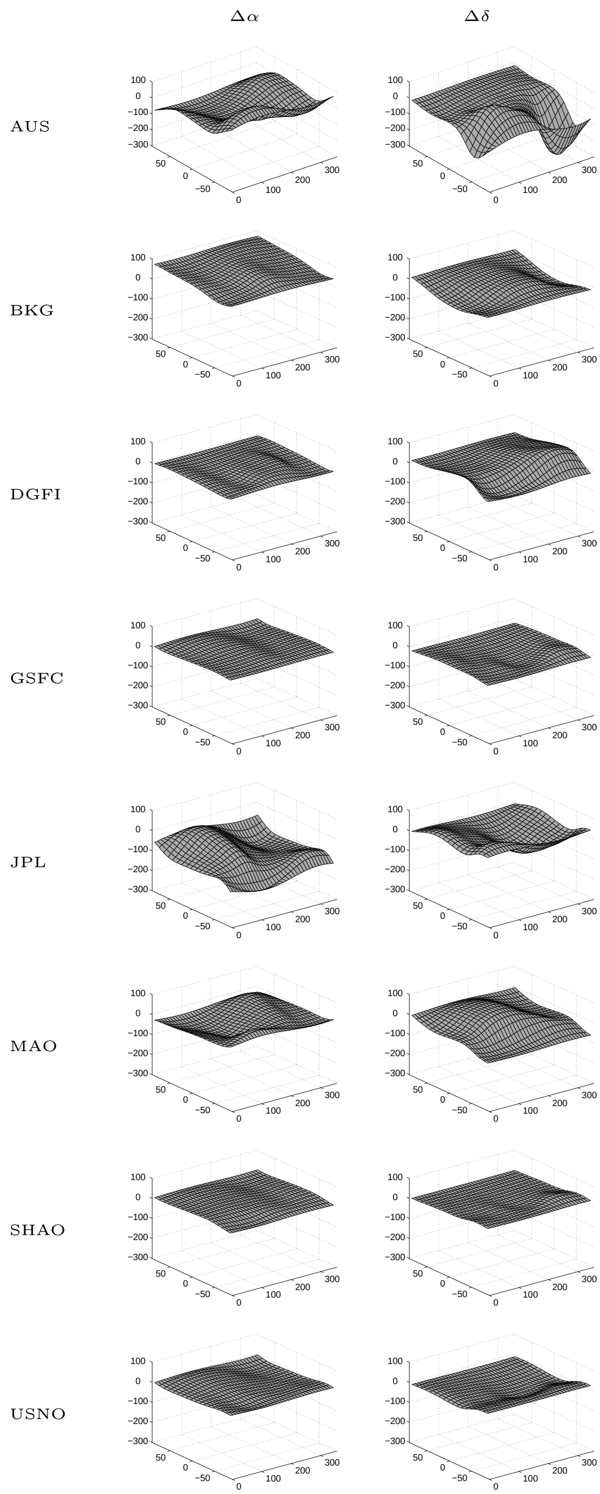

Figure 7: Systematic differences between the input catalogues and combined catalogue RSC(PUL)07C02. Horizontal axes show right ascension (*right*) and declination (*left*) in degrees. Unit: μas.

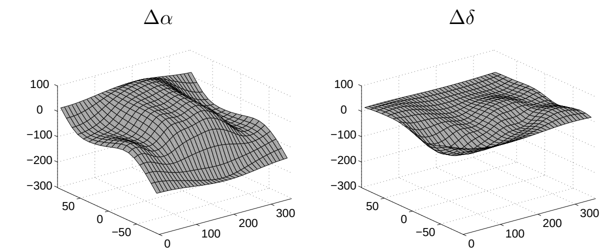

Figure 8: Differences between RSC(PUL)07C02 and ICRF. Horizontal axes show right ascension (*right*) and declination (*left*) in degrees. Unit: μas.

coordinates, in particular a method used so-called arc approach developed by Yatskiv & Kur'yanova (1990).

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